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Append-Only Hash Chain Verification at Scale: Performance Analysis of Million-Entry Ledgers

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Abstract

Hash chain verification is the fundamental integrity-checking operation for cryptographic ledgers, requiring sequential recomputation of all entry hashes. As ledgers scale to millions of entries, verification time becomes a critical operational constraint. This paper presents a comprehensive performance analysis of SHA3-256 hash chain verification at scale, using million-entry AIOSS ledgers on AMD EPYC 7702 and ARM Ampere Altra processors. We evaluate three verification strategies: sequential full verification, batched Merkle subtree verification, and parallel chunked verification with cross-validation. Our results demonstrate that sequential verification of one million entries completes in 2.47 seconds on EPYC 7702 (64 cores, 2.0 GHz) utilizing single-threaded execution, with throughput of 405,000 entries per second. Parallel verification using chunked Merkle trees achieves 4.8x speedup on 8 cores, completing verification in 0.51 seconds. We analyze the I/O bottleneck characteristics, demonstrating that NVMe storage bandwidth (7.5 GB/s) is not the limiting factor for ledgers under 10 million entries. We further evaluate memory-mapped I/O, direct I/O, and asynchronous I/O strategies, finding that mmap provides optimal performance for verification of ledgers exceeding 100 MB. The paper presents a cost model for verification operations applicable to regulatory audit scenarios requiring periodic integrity verification of growing ledgers.

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1. Introduction

Hash chain verification is the process of recomputing the hash chain of a ledger and comparing against stored hash values to detect tampering. For an append-

only ledger with n entries, sequential verification requires n SHA3-256 hash computations, each dependent on the previous entry's hash. This serial dependency prevents straightforward parallelization, making verification time linear in ledger size.

As AIOSS ledgers grow to millions of entries (a typical enterprise AI deployment generates 50,000-100,000 audit events per day), verification time becomes operationally significant. A one-million-entry ledger requiring 30 minutes to verify would be impractical for daily integrity checks. Understanding the performance characteristics of hash chain verification across hardware platforms is therefore essential for deployment planning.

This paper presents benchmark results for AIOSS hash chain verification on enterprise server hardware, analyzing the impact of CPU architecture, I/O subsystem, verification strategy, and entry size distribution. We develop a cost model that enables practitioners to estimate verification time for their specific deployment parameters.

2. Literature Review

2.1 Hash Chain Verification Performance

Early analysis of hash chain performance focused on Bitcoin block validation. Karame et al. (2012) measured Bitcoin block verification time on commodity hardware, finding that signature verification dominated (85% of total time). More recently, Han et al. (2020) analyzed Ethereum block verification, showing that state transition verification now dominates due to smart contract execution. These analyses focus on blockchain consensus verification rather than pure hash chain integrity.

For tamper-evident logging systems, Crosby and Wallach (2009) demonstrated that hash chain verification scales linearly with entry count and proposed skip list structures for logarithmic verification of authenticity proofs. Pullkis et al. (2020) extended this analysis to cloud-based logging infrastructure, showing that I/O latency dominates verification time for ledgers exceeding 100,000 entries.

2.2 Hash Function Performance Benchmarking

Guido et al. (2019) provided comprehensive benchmarking of cryptographic hash functions on modern CPUs, including SHA3-256, SHA2-256, BLAKE2, and BLAKE3. Their results show SHA3-256 achieving 0.31 GB/s on Intel Skylake, while SHA2-256 achieves 0.84 GB/s. Alwen et al. (2021) analyzed sequential hashing throughput, demonstrating that memory-hardness properties significantly impact performance in multi-threaded scenarios.

The SUPERCOP benchmarking framework (Bernstein & Lange, 2020) provides fine-grained hash function performance data across hundreds of platforms.

eBACS (ECRYPT Benchmarking of Cryptographic Systems) continuously updates these benchmarks, providing a valuable resource for performance estimation.

2.3 Parallelization Strategies for Hash Chains

Sequential dependency in hash chains appears to prevent parallelization, but several techniques have been proposed. Tomescu et al. (2020) introduced Merkleized hash chains where each log entry includes a Merkle proof of its position, enabling parallel verification of disjoint segments. Crosson and Liskov (2022) formalized parallel hash chain verification using subtree hashing, demonstrating O(log n) verification time with O(n) processors. Alwen et al. (2021) showed that hash chains using tree-based constructions achieve near-linear speedup on multi-core processors for verification.

3. Technical Analysis

3.1 Verification Time Model

The total verification time T for a ledger of n entries is:

$$T(n) = T_{\text{read}}(n) + n \cdot (T_{\text{hash}} + T_{\text{compare}}) + T_{\text{overhead}}$$

where: - $ T_{read}(n) $ is I/O time to read n entries - $ T_{hash} $ is time per SHA3-256 computation on the CPU - $ T_{compare} $ is time to compare computed vs. stored hash (32-byte memcmp) - $ T_{overhead} $ includes parsing, format detection, and state initialization

The I/O time depends on the access pattern:

$$T_{\text{read}}(n) = \max\left(\frac{S_{\text{entry}} \cdot n}{B_{\text{seq}}}, L_{\text{seek}} + \frac{S_{\text{entry}} \cdot n}{B_{\text{rand}}}\right)$$

where $ S_{entry} $ is entry size, $ B_{seq} $ and $ B_{rand} $ are sequential and random read bandwidth, and $ L_{seek} $ is seek latency.

3.2 Experimental Setup

Benchmarks were conducted on:

System A (x86_64): - CPU: AMD EPYC 7702 (64 cores, 2.0 GHz base, 3.35 GHz boost) - RAM: 256 GB DDR4-3200 - Storage: Samsung PM9A3 NVMe (7.5 GB/s sequential read) - OS: Ubuntu 22.04 LTS, Linux 6.2

System B (aarch64): - CPU: Ampere Altra Q80-30 (80 cores, 3.0 GHz) - RAM: 256 GB DDR4-3200 - Storage: Samsung PM9A3 NVMe (7.5 GB/s sequential read) - OS: Ubuntu 22.04 LTS, Linux 6.2

Ledger configurations tested: - Small entries: 256 bytes payload (representative of telemetry events) - Medium entries: 4 KB payload (representative of compliance records) - Large entries: 64 KB payload (representative of AI inference logs)

3.3 Sequential Verification Results

Ledger size: 1,000,000 entries, medium payload (4 KB). Total ledger size: ~4 GB.

Platform	Verification Time	Throughput (entries/s)	Hash Rate (MB/s)
EPYC 7702 (1T)	2.47 s	405,000	1,580
EPYC 7702 (8T)	1.23 s	813,000	3,160
Altra (1T)	3.12 s	320,000	1,250
Altra (8T)	1.58 s	633,000	2,530

Note: single-threaded (1T) verification is fully sequential. Multi-threaded improvement comes from I/O prefetching and entry parsing, not from parallel hash chain computation.

3.4 Merkle Batching Strategy

We implement Merkle batching by dividing the ledger into fixed-size batches and computing a Merkle tree for each batch's entry hashes:

```
Algorithm 1: Merkle-Batched Hash Chain Verification
Input: Ledger entries E[0..n-1], batch size k
Output: Verification result

1: num_batches ← ceil(n / k)
2: batch_roots ← array[num_batches]
3: parallel for b in 0..num_batches-1 do
4:   start ← b * k
5:   end ← min(start + k, n)
6:   chain_hash ← (b = 0) ? GENESIS_HASH : batch_roots[b-1]
7:   for i in start..end-1 do
8:     h ← SHA3-256(encode(E[i]))
9:     chain_hash = h
10:  end for
11:  batch_roots[b] ← SHA3-256(chain_hash || b)
12: end parallel for
13: // Verify cross-batch linkage
14: for b in 1..num_batches-1 do
```

```
15:   expected ← SHA3-256(E[b*k-1].hash || b)
16:   if expected  batch_roots[b-1] return false
17: end for
18: return true
```

Batch verification results (EPYC 7702, 1M entries, 4 KB payload):

Batch Size	Cores	Time (s)	Speedup	Memory (MB)
1,000	4	0.82	3.01x	64
1,000	8	0.51	4.84x	128
10,000	4	0.94	2.63x	32
10,000	8	0.58	4.26x	64
100,000	4	1.12	2.21x	16
100,000	8	0.72	3.43x	32

Optimal batch size is 1,000 entries, achieving 4.84x speedup on 8 cores.

3.5 I/O Bottleneck Analysis

For small entries (256 B payload), I/O becomes the bottleneck beyond 8 million entries:

Entries	Ledger Size	I/O Time (NVMe)	Verify Time (8T)	I/O %
1 M	0.4 GB	0.05 s	0.51 s	9.8%
10 M	4 GB	0.53 s	5.12 s	10.4%
100 M	40 GB	5.33 s	51.71 s	10.3%

For large entries (64 KB payload), I/O dominates beyond 2 million entries:

Entries	Ledger Size	I/O Time (NVMe)	Verify Time (8T)	I/O %
1 M	64 GB	8.53 s	51.72 s	16.5%
10 M	640 GB	85.33 s	129.87 s	65.7%
100 M	6.4 TB	853.33 s	932.45 s	91.5%

4. Current State of the Art

4.1 Alternative Verification Approaches

Zero-knowledge proofs (ZKPs): Bunz et al. (2020) demonstrated FlyClient, enabling super-light clients to verify blockchain state through probabilistic sampling. For hash chains, this would reduce verification complexity from O(n) to O(log n). However, ZKP generation overhead remains high (minutes for large statements).

Verifiable delay functions (VDFs): Boneh et al. (2018) proposed using VDFs for sequential work verification. Wesolowski (2019) VDFs could enable "proof of sequential work" for hash chains, providing compact verification of correct sequential execution.

Trusted execution environments (TEEs): Verifying hash chain computation within TEEs (Intel SGX, AMD SEV) provides hardware attestation of correct verification. But TEEs introduce trusted computing base concerns.

4.2 Industry Practice

Production logging systems (Splunk, Elastic) typically avoid hash chain integrity at scale due to performance concerns. Instead, they rely on access control and audit logging of log modifications. The Certificate Transparency ecosystem (Google) verifies billions of entries daily using Merkle tree verification, demonstrating that hash-based integrity at scale is feasible with appropriate data structures.

5. Relevance to AIOSS

5.1 AIOSS Verification Implementation

AIOSS implements three verification modes:

1. **Full verification:** Sequential recomputation of the entire hash chain (Algorithm 1)
2. **Quick verification:** Verification of the last N entries plus the state proof
3. **Batch verification:** Parallel Merkle-batched verification (Algorithm 2)

CLI interface:

```
aioss verify --ledger ledger.aioss             # full verification
aioss verify --ledger ledger.aioss --quick     # last 1000 entries
aioss verify --ledger ledger.aioss --parallel  # Merkle batched
```

5.2 Deployment Recommendations

Based on our benchmarking, we recommend: - Ledgers $<$ 10M entries: Full sequential verification (daily) - Ledgers 10M-100M entries: Batched parallel verification (daily) - Ledgers $>$ 100M entries: Quick verification for daily checks, full verification weekly

These recommendations ensure regulatory compliance with FedRAMP (daily integrity checks required) and SOC2 (periodic integrity verification) while maintaining operational feasibility.

6. Future Directions

6.1 GPU-Accelerated Hash Chain Verification

GPUs offer massive parallelism for hash computation. SHA3-256's sponge construction is particularly amenable to GPU acceleration. Kalra et al. (2023) demonstrated GPU-accelerated SHA3-256 achieving 37 GB/s on NVIDIA A100, potentially reducing billion-entry hash chain verification to seconds.

6.2 Learned Verification Models

Machine learning approaches to predict verification time based on entry size distribution could enable dynamic scheduling of integrity checks. Wang et al. (2024) applied transformer models to predict blockchain verification time with 94% accuracy.

6.3 Probabilistic Verification

For non-critical integrity checks, probabilistic sampling verification (checking a random subset of entries) provides statistical tamper detection guarantees. Gervais et al. (2016) analyzed sampling strategies for blockchain lightweight clients.

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